

Progress in Systems Studies

***Advanced Fuel Cycle Initiative
Semi-Annual Review Meeting
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Operated by The University of Chicago
for the U.S. Department of Energy***



FY03 Focus Areas

Transmutation Systems Studies had three components this year:

- **Transmutation Criteria**
 - Specify quantitative objectives
- **Transmutation Options**
 - Assess capabilities of various systems
- **Transmutation Analyses**
 - Specific analyses to support technical systems

Three separate areas were also pursued:

- **Integrated Model Development**
 - Assess bounding scenarios and initiate economics analysis
- **Repository Benefits**
 - Clarify AFCI impact on repository performance
- **Nonproliferation and Safeguards**
 - Develop integrated safeguards approach for fuel cycle

Overview of Systems Analysis Progress

Timely progress achieved in all focus areas

- **Technical accomplishments documented in AFCI reports**
- **Three topics will be highlighted in subsequent talks**
 - Repository benefits – W. Halsey
 - Transmutation options – R. Hill
 - Analysis of Pu+Np recycle in LWRs – M. Todosow

In this talk, recent work which clarifies the AFCI impact/benefits and quantifies the program goals will be reviewed:

- **Summer scenarios study**
 - Dynamic analysis and comparison of key fuel cycle scenarios
- **Transmutation criteria workshop**
 - Clarification of approach and specification of quantitative goals

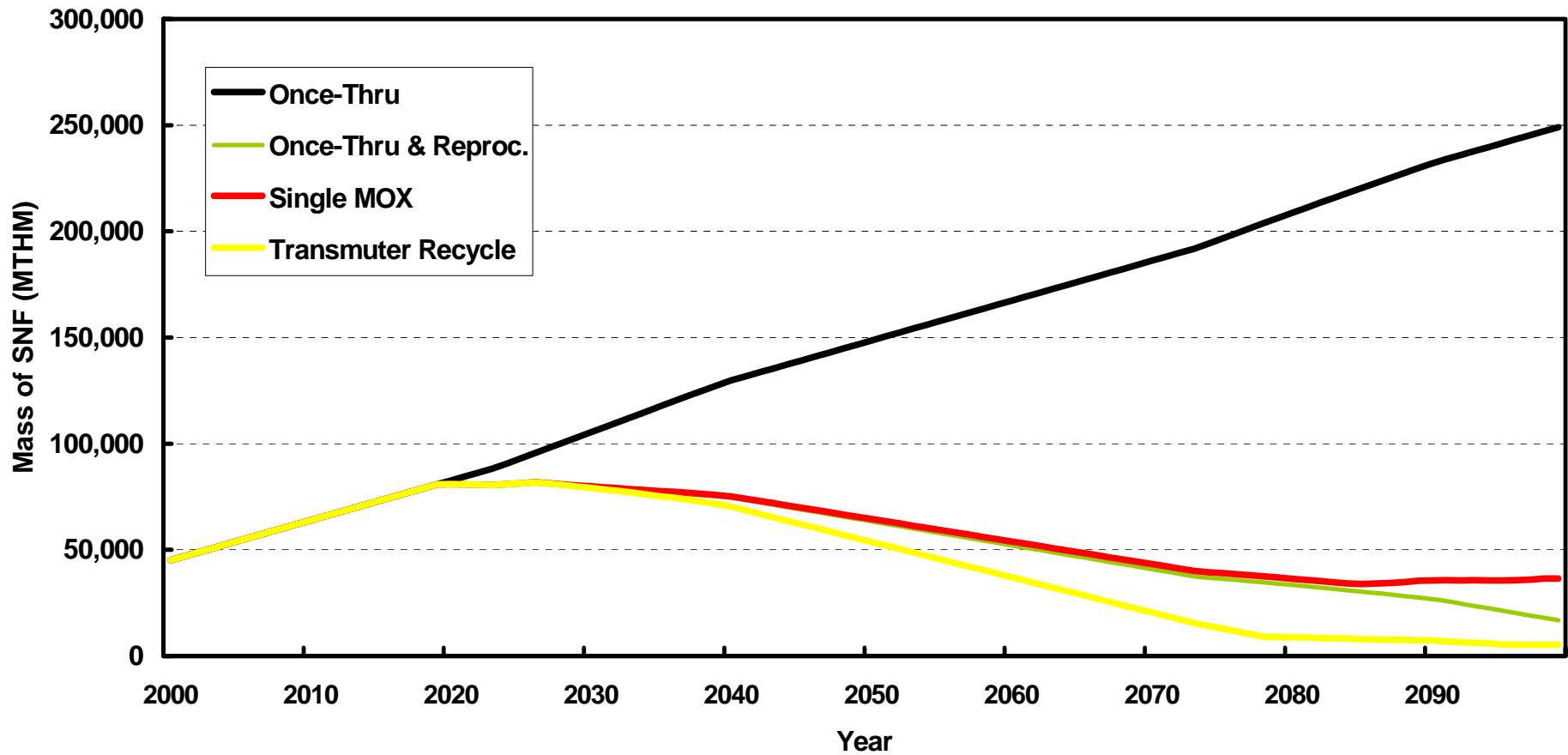
Objectives of Summer Scenarios Study

- **Several goals motivate this analysis effort**
 - Frame quantitative goals for AFCI
 - Highlight urgency of the waste management issues
 - Compare diverse fuel cycle scenarios
- **Fuel cycle impact evaluated for limited set of scenarios**
 - Once-through and separations only
 - Single MOX recycle
 - Single and double tier transmutations systems
- **Dynamic analysis of fuel cycle performance**
 - Consider stable and growth scenarios
 - Estimate of infrastructure requirements
 - Impact of reprocessing on spent fuel characteristics
 - Tracking of material inventories throughout entire fuel cycle

Impact of Recycle on the LWR Spent Nuclear Fuel Inventory

- **With continued nuclear power production, the spent nuclear fuel (SNF) inventory grows significantly**
 - Yucca Mountain inventory (65,000 MT initial HM) reached in roughly 2010
 - With once-through fuel cycle, increases by factor of 4 by 2100
 - With modest (1.5%) growth, increases by factor of 7
- **Recycle can significantly reduce the mass of SNF**
 - Mass is reduced primarily by removal of uranium which is processed into low level waste
 - *In long run, single MOX recycle can reduce mass by 5X*
 - *Further reduction achieved with multi-recycle*
 - Processing capacity requirements were scoped
 - *For no growth, need 2,000-3,000 MT/yr*
 - *For modest growth, need 2,000-4,500 MT/yr*
- **However, mass reduction does not address the inventory of key radioactive materials or repository criteria (e.g., heat load)**

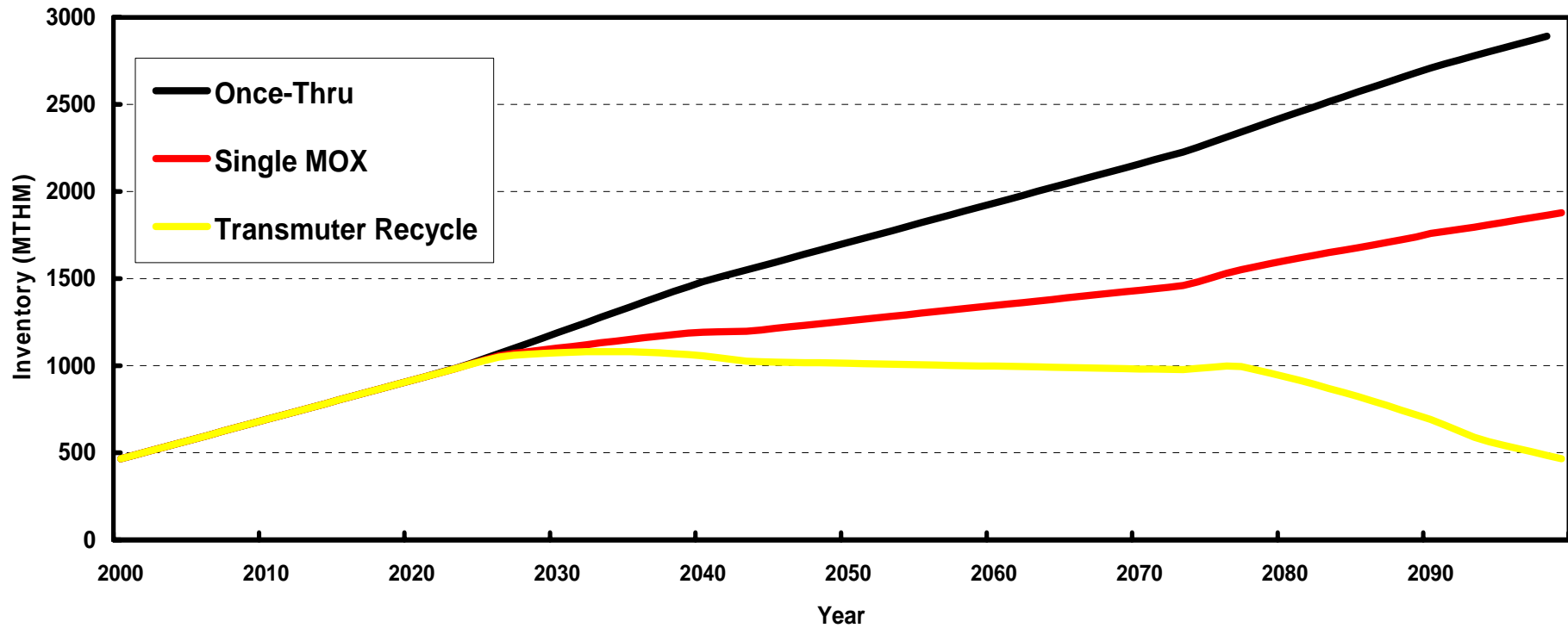
Spent Fuel Inventory - No Growth Scenario



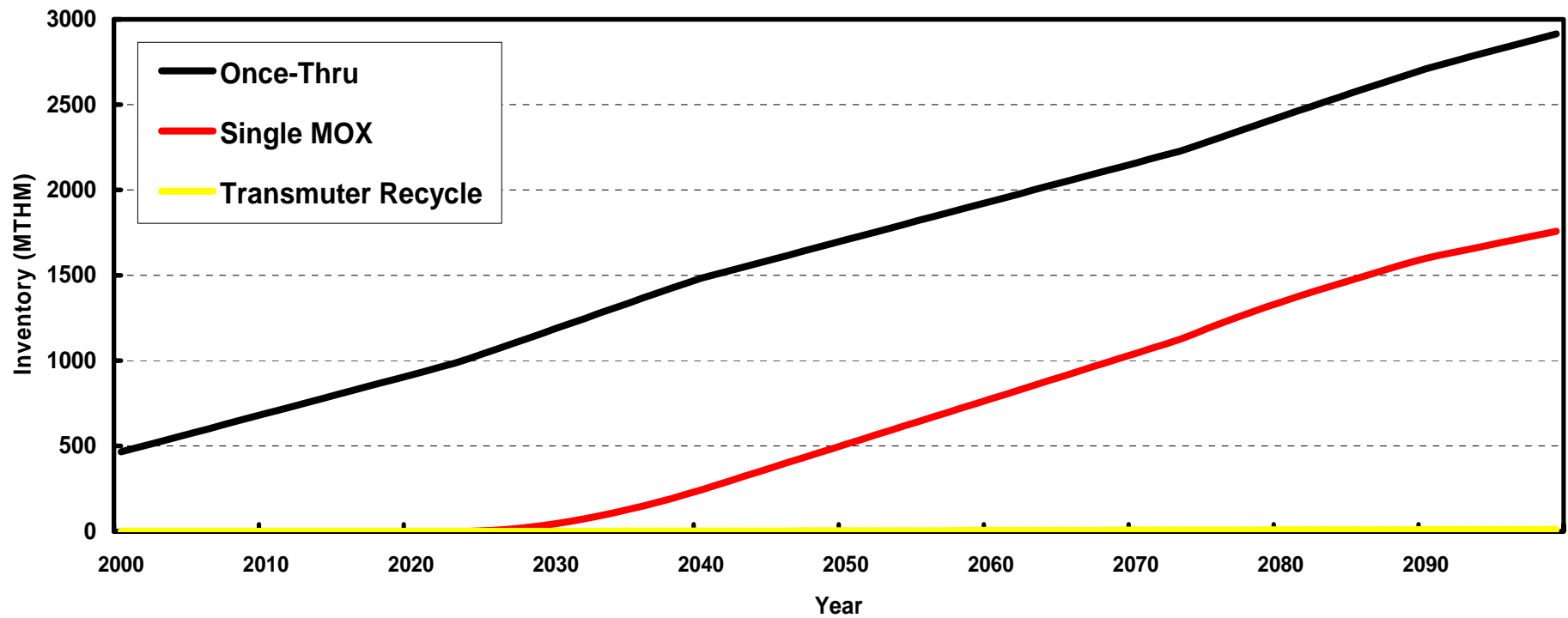
Impact of Recycle on Key Radioactive Species

- **The inventory of key radioactive elements is hard to reduce**
 - MOX recycle can stabilize the plutonium inventory
 - *Effect is temporary for single recycle*
 - *Begins to increase once spent MOX is accumulated*
 - *Minor actinide inventory steadily increases*
 - Plutonium inventory can be reduced in multi-recycle scenarios
 - *Using advanced thermal reactor recycle or fast transmuters*
 - *Inventory management requires significant burner capacity*
 - *Timing is dictated by both power replacement and startup inventory requirements*
 - Important to distinguish location of plutonium inventory
 - *Destined for waste in once-through fuel cycle*
 - *Single cycle delay and then to waste for MOX*
 - *Contained in processing/reactor for multi-recycle*
 - Only losses destined for waste disposal

Pu+Np Inventory - No Growth Scenario



Pu+Np Inventory to Waste



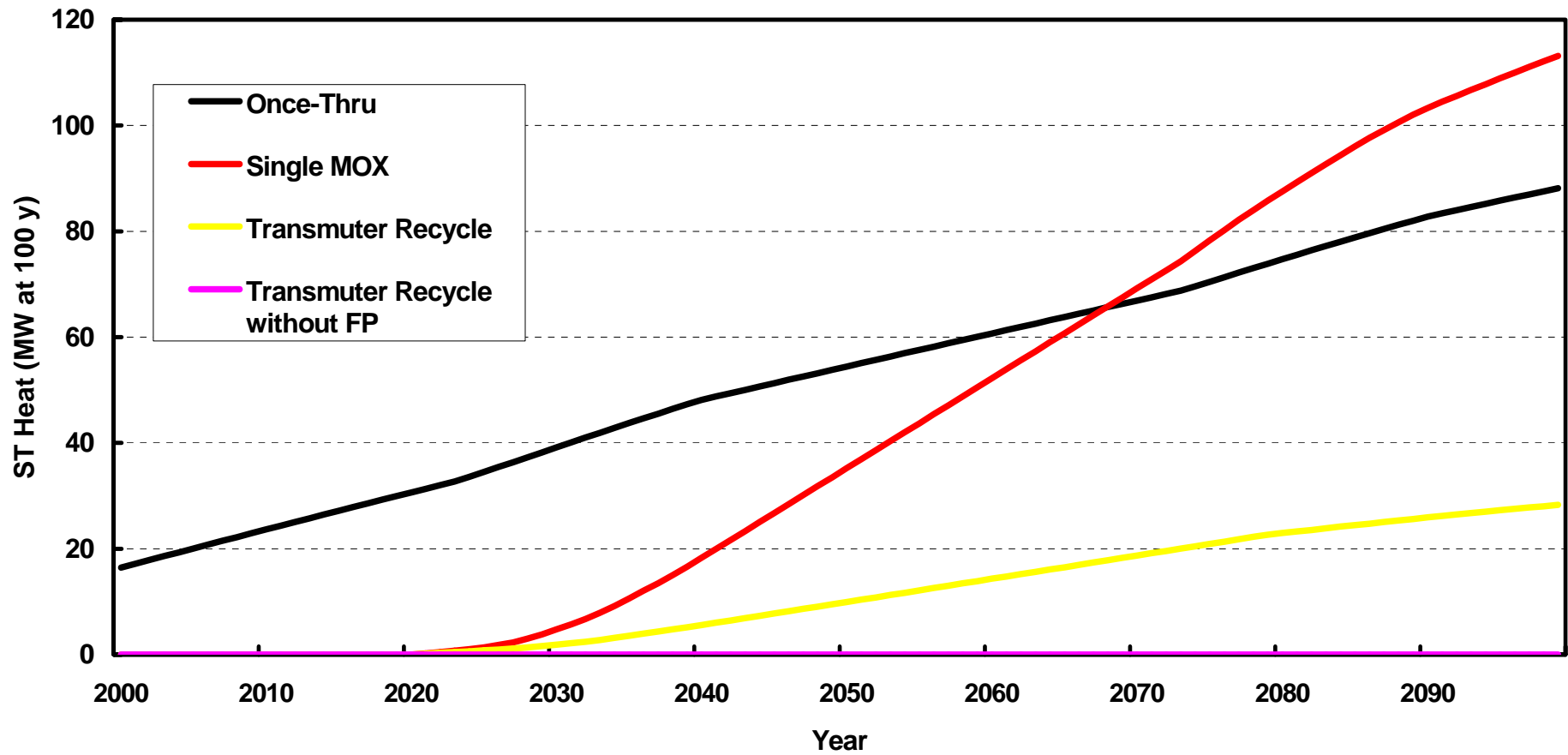
Repository Performance Measures

- **A wide variety of measures have been proposed to quantify and compare repository performance**
 - Radiotoxicity of disposed waste
 - Dose rate from release at specified repository boundary
 - Waste heat at variety of cooling times (handling, storage)
- **For current repository design, waste loading is constrained by thermal limits**
 - Thermal analyses have shown that limit for direct disposal is between-drift temperature (peaks at ~1500 years)
 - Wall temperature (peaks after ventilation) also important
 - Note that short term operations are strongly affected by short term heat load
- **Current work has focused on decay power comparisons which are indicative of impact on repository capacity**
 - Short-term decay power at 100 years after placement
 - Long-term integrated heat, from 100-1500 years

Impact of Recycle on Repository Performance

- **To benefit repository thermal criteria, requires exclusion of transuranics (TRU) from the waste**
 - Plutonium and minor actinides dominate short-term heat, long-term heat, and repository dose
 - MOX recycle delays TRU waste, but does not eliminate
 - *Higher than once-through because of Pu-238 build-up*
 - Multi-recycle gives large reduction of long-term heat load as only TRU losses go to waste
 - Once bulk of TRU is removed, Cs+Sr contribution to the post-closure (100 y) heat load becomes important
 - *Heat and dose from fission products (e.g., Cs&Sr) is quite important for handling period before closure*

Short-term Decay Power in Repository



General Conclusions of Scenario Studies

- **With extended nuclear power production, large inventories of spent nuclear fuel must be managed**
 - Many times the proposed capacity of current repository
- **Fuel reprocessing can significantly reduce the spent nuclear fuel inventory (mass reduction)**
 - Processing infrastructure of at least current spent fuel discharge rate (2,000 MT/yr) is required
- **Transmutation systems (advanced thermal or fast) are required to reduce inventory of key species (e.g., plutonium)**
- **Significant repository benefits for TRU removal**
 - MOX recycle delays, but does not eliminate heat loads
 - Multi-recycle achieves significant reduction in waste heat
- **Delays in implementation will have significant consequences**
 - For 10 year delay, 20,000 MT more spent fuel must be stored
 - Serious impact on government responsibility for waste disposal
 - Adverse impact on new plant construction without robust waste solution

Conclusions of Summer Study

- **Original goal to reduce the inventory of spent fuel *and* key waste species is difficult to achieve**
 - Mass of spent fuel is reduced by reprocessing
 - Inventory of plutonium and/or minor actinides can only be reduced by large infrastructure of transmuter (either advanced thermal or fast) systems
 - *Both reprocessing capacity and transmuter inventory requirements constrain the introduction rate*
 - Recommendation is to re-define goal to cap growth (stabilize) of the plutonium and/or minor actinide inventory
- **In contrast, significant reduction in key repository performance parameters can be achieved**
 - Large inventory is “stored” in the transmuter fuel cycle, while power is being generated
 - Decay heat sent to waste can be drastically reduced

Transmutation Criteria Workshop

Objectives of the task:

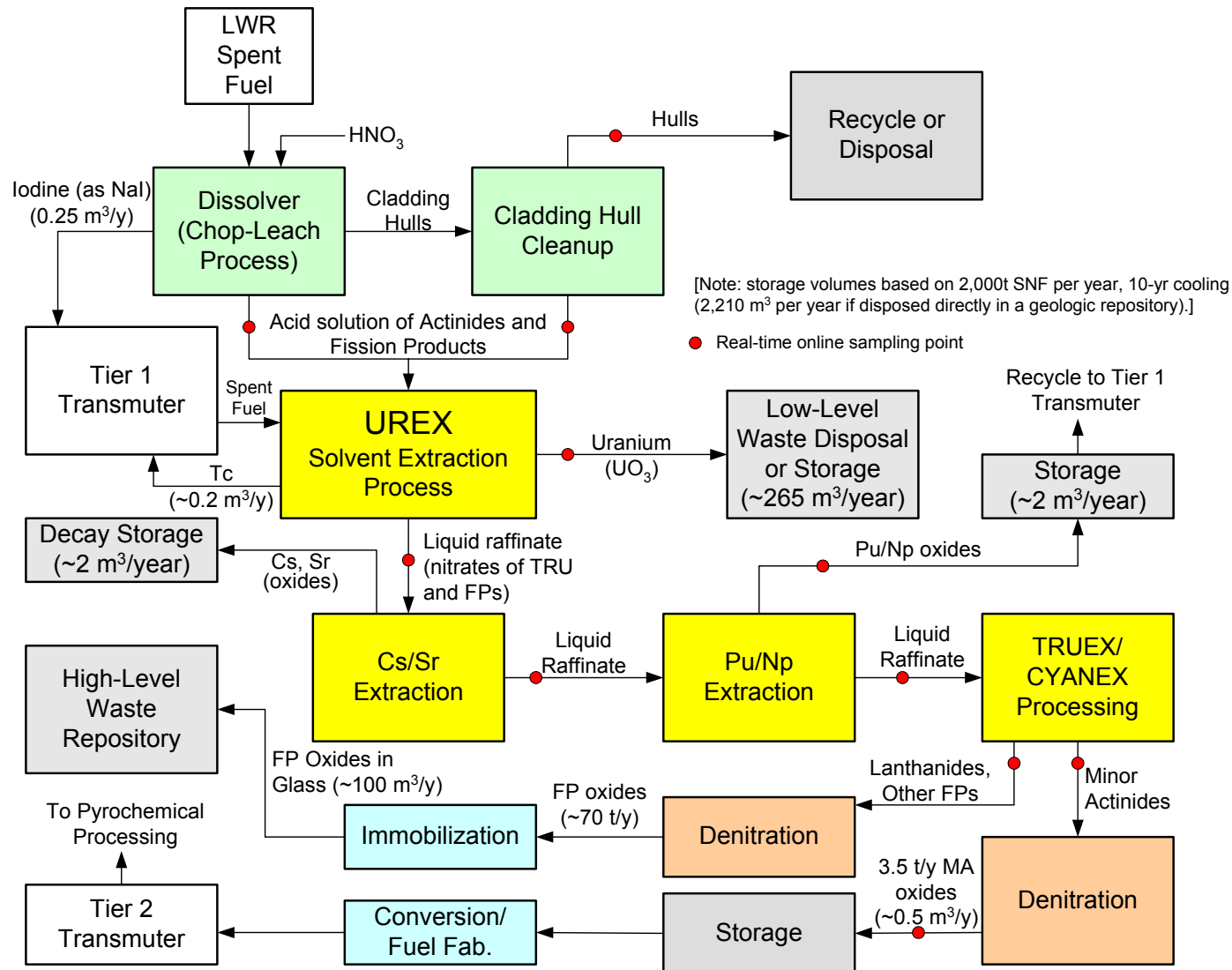
- **Integrate current knowledge to better specify the reference AFCI flowsheet**
 - Material Pathways (storage, transmutation)
 - Technological criteria
- **Define reference pathways and criteria**

Approach:

- **Analysis of the flowsheet revealed 10 top level issues that require clarification**
- **For each, one or two experts were designated**

Issue**Responsible Individuals****Proliferation Resistance****Waltar/Roglans****Repository Benefits****Halsey/Wigeland****Separations Criteria****Laidler****Uranium Disposal or Recycle****Collins****Iodine Disposal or Recycle****Hill****Tc Disposal or Recycle****Hill****LWR Recycle Objectives****Bathke****Cs/Sr Recovery Objectives****Herring****Cm Storage or Recycle****Collins****TRU Recycle Objectives****Halsey/Wigeland**

UREX+ Process for LWR Spent Fuel



Proliferation Resistance

- **Expect that proposed dual tier fuel cycle cannot be made intrinsically proliferation resistant**
- **Some benefits from co-recycle of Np and Pu, but well below spent fuel standard**
- **Place emphasis on improving extrinsic proliferation resistance**

Recommendations:

- Need to design facilities that are easy to safeguard without adding excessive cost
- AFCI needs to be given the opportunity to review and challenge, if necessary, the proliferation metrics under development in Gen-IV
- Better technologies need to be developed to monitor process streams and detect variations with high fidelity

Separated Uranium Disposal Pathways

- **Disposal as Class C Waste**
- **Re-enrich and use in UO_2 fuel**
 - No significant technical hurdles to re-use
 - Significant savings in enrichment costs
 - Additional purification steps are expected to be cheaper than potential savings

Recommendation

- **Pursue the re-use path after thorough economic assessment**

Long Lived Fission Products: Storage or Transmutation

- Dose due to Tc/I is well below statutory limits. Might become issue if capacities expanded
- Transmutation rate must be >90%
 - Major infrastructure requirements
 - Expect technical difficulties
 - *Target fabrication and irradiation behavior*
 - *Multirecycle approach*

Recommendation

- Do not pursue the recycle path
- Develop robust waste forms

Cs/Sr Recovery

Objective: heat generated by remaining Cs/Sr equivalent to heat generated by all other FP's at time t

t (year)	Recovery factor
10	90%
30	97%

Note that separations costs should not significantly change for recovery factors up to 99%.

Recommendation: aim at recovery factor in 97% to 99% range, with goal of 99%.

Conclusions of Criteria Workshop

- **Reference pathways have been recommended**
 - U recycle
 - I and Tc storage
 - LWR multirecycle?
 - Cm recycle
- **Reference quantitative criteria have been recommended**
 - Separations
- **Systematic studies are required**
 - Repository benefits
 - Economics

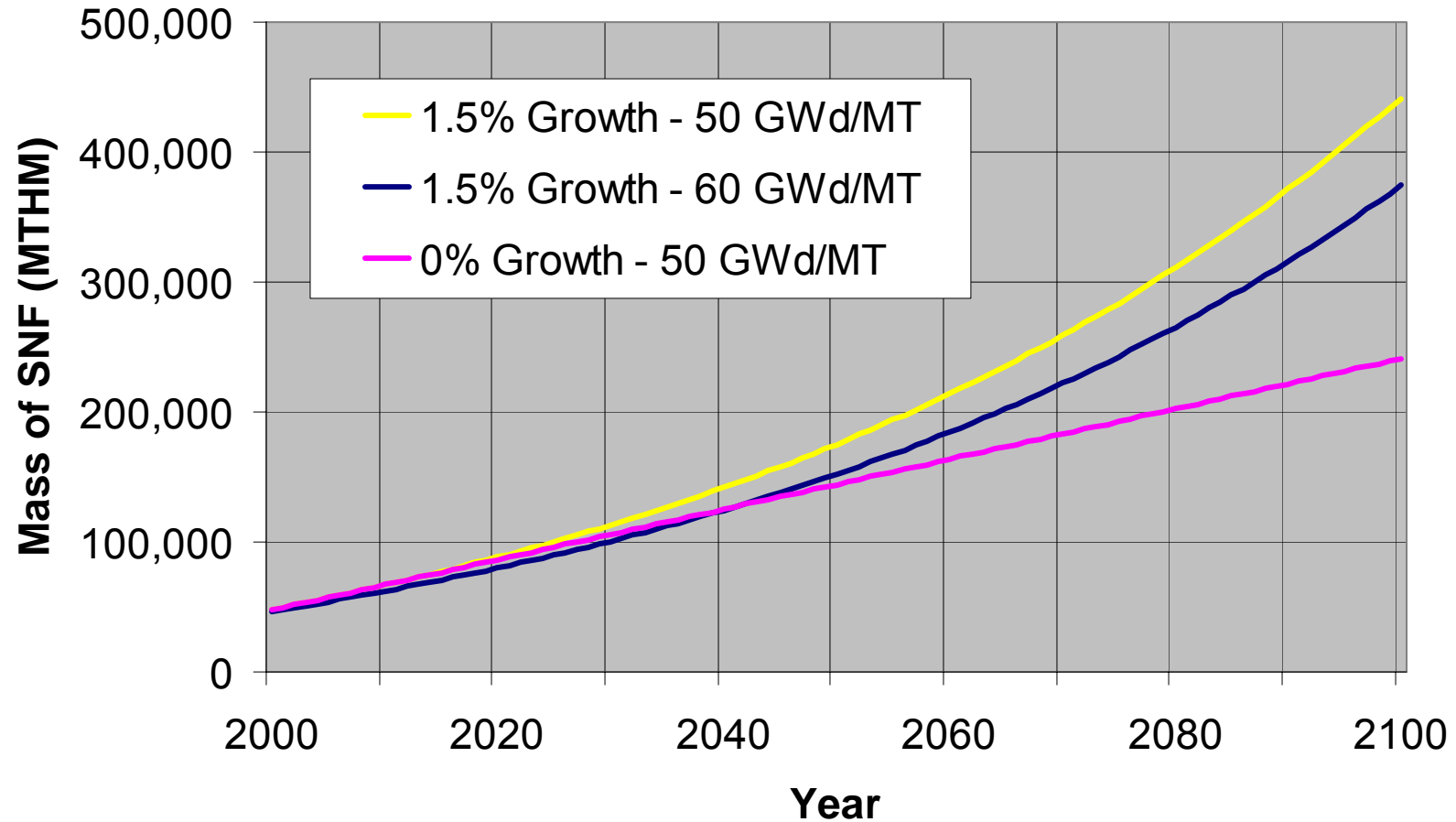
Major Outcomes for FY03 System Studies

- **Systematic approach to the analysis of the technical option space**
- **Quantification of repository benefits has been initiated**
- **Reference technical criteria and material disposal paths have been established**
- **Tools for dynamic scenario analyses have been exercised. Preliminary study confirm intuitive judgement**
- **Major priorities for 04**
 1. Establish reference time dependant scenarios
 2. Initiate cost/benefit analyses for these scenarios
 3. Establish criteria and materials pathways for these scenarios
 4. Continue exploring transmutation option space.

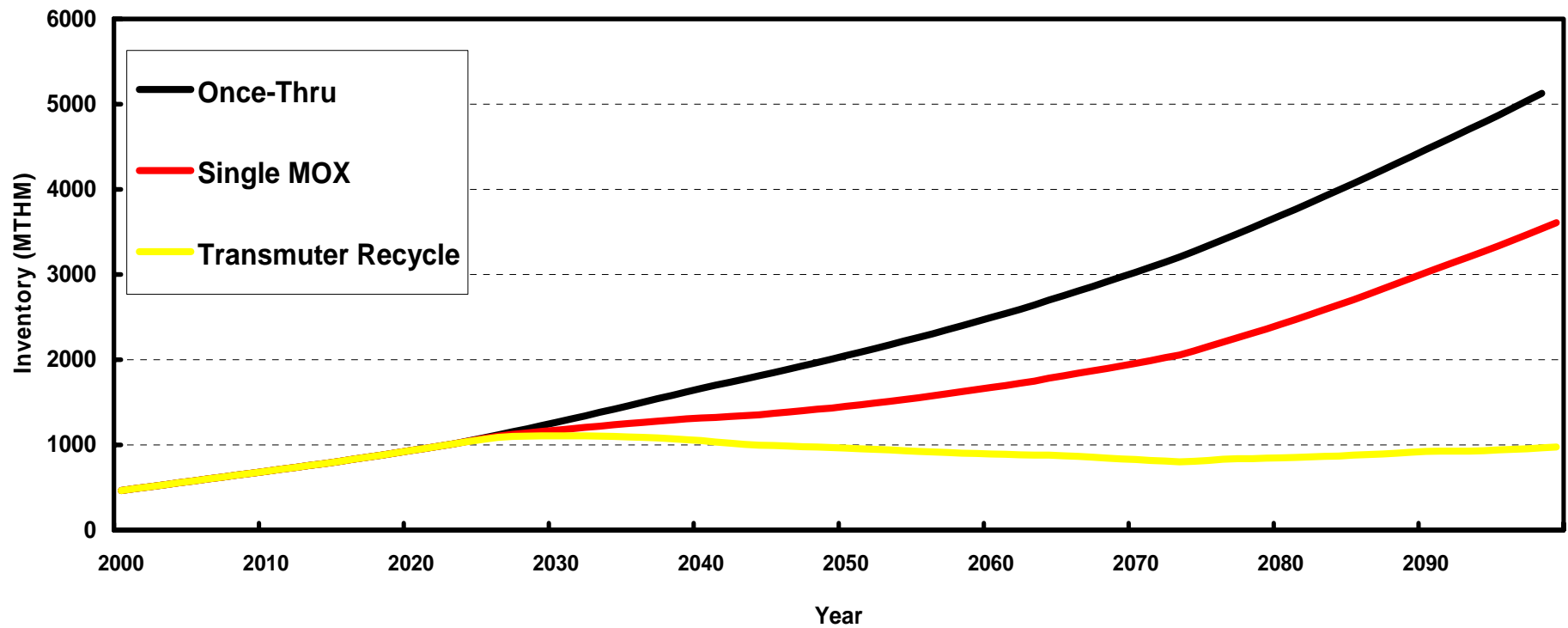
● **BACKUP**

- **Summer Study - 5**
- **Xmut Criteria Workshop – 7**

LWR Spent Fuel Inventory

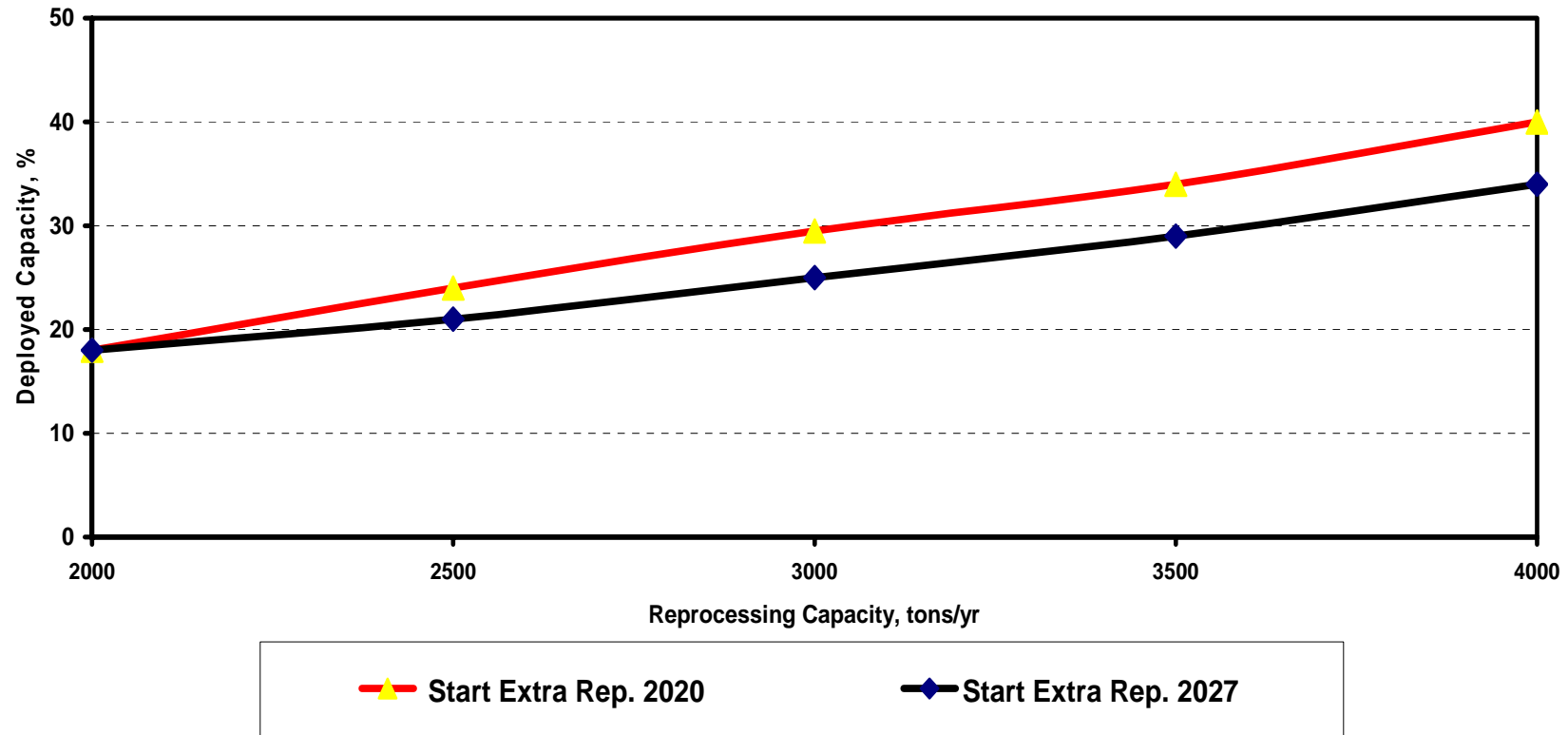


Pu+Np Inventory - Modest Growth Scenario

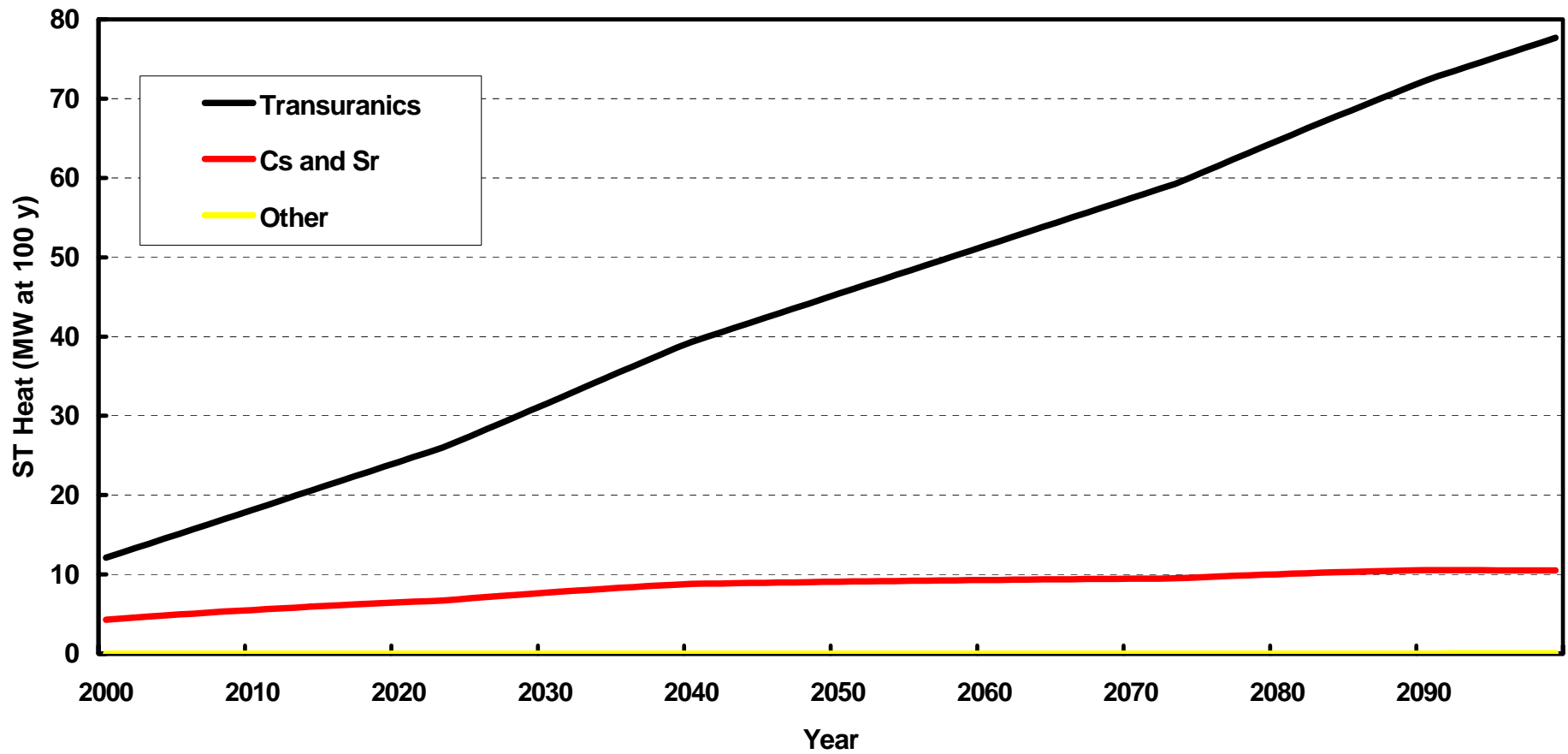


Transmuter Capacity Requirements

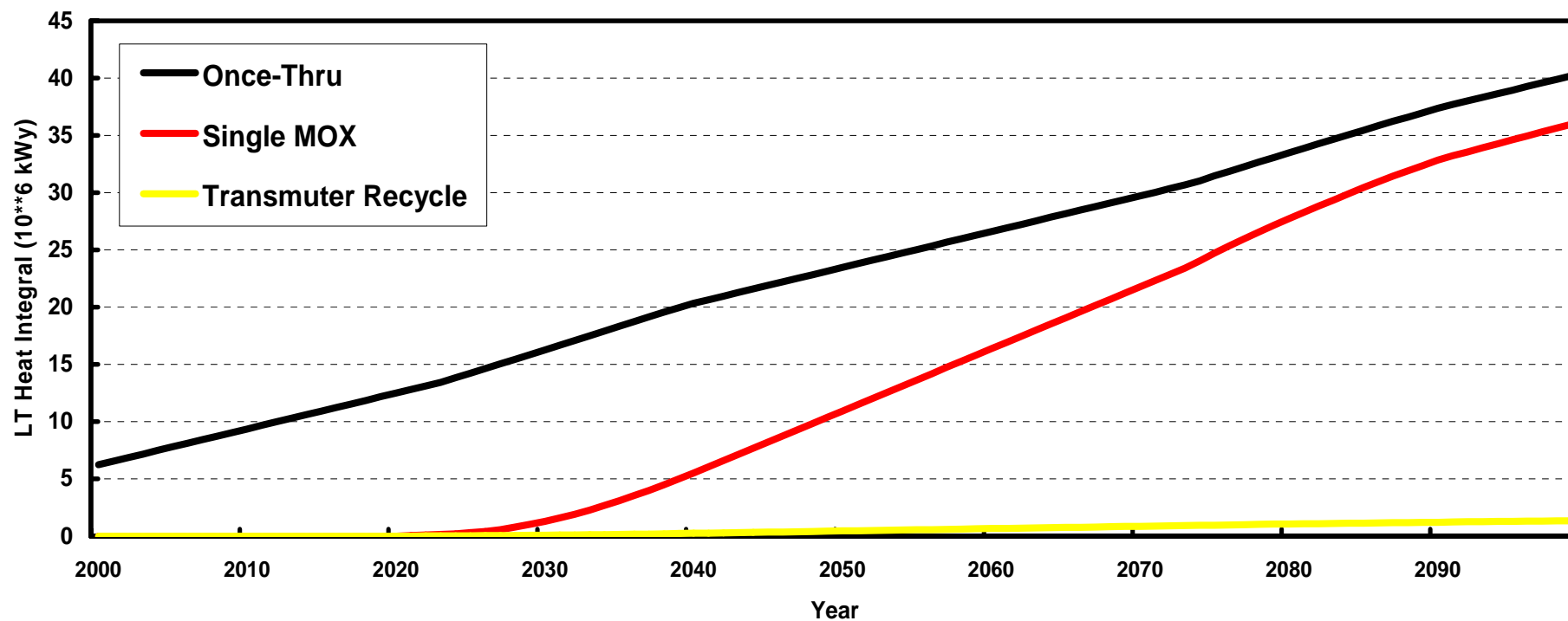
Maximum FR Deployed Capacity Fraction as a Function of Reprocessing Capacity



Short-term Decay Power Contributions



Long-term Heat Load in Repository



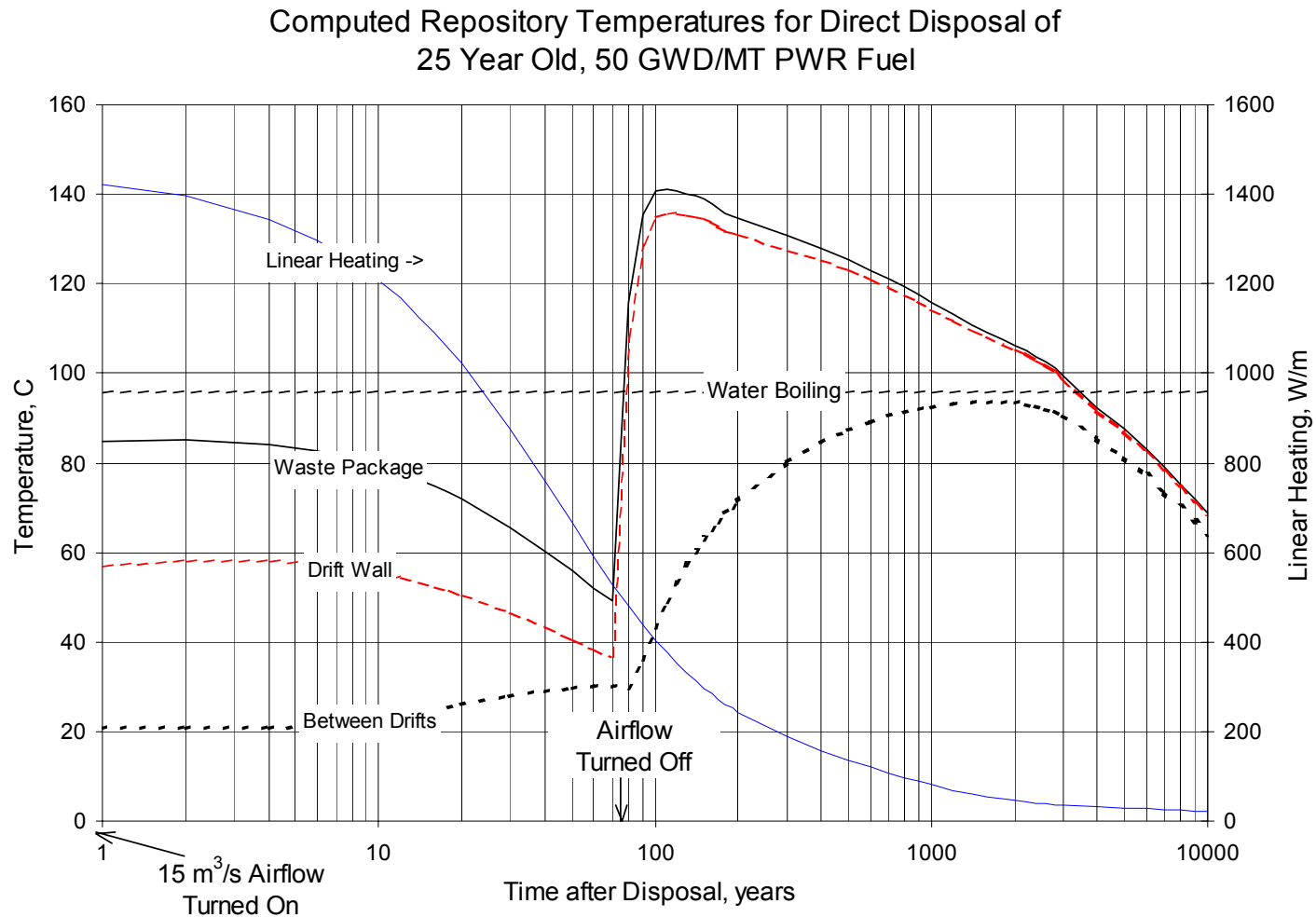
Repository Objectives

- Focus of program is on avoiding need for a second repository
- Thermal studies of YM were presented that indicate that heat loading is a limiting parameter for the total waste storage capacity
 - Mid point between drifts < 96 C
 - Drift wall < 200 C
- First limit is reached after ~ 1500 years
 - Capacity can be increased by eliminating transuranics (3 to 5)
 - Second limit then becomes critical: capacity can be increased up to 100 fold by eliminating Cs/Sr (separations + decay; ventilation?)

(Note: the combined effect is much larger than the sum of the separated effects)

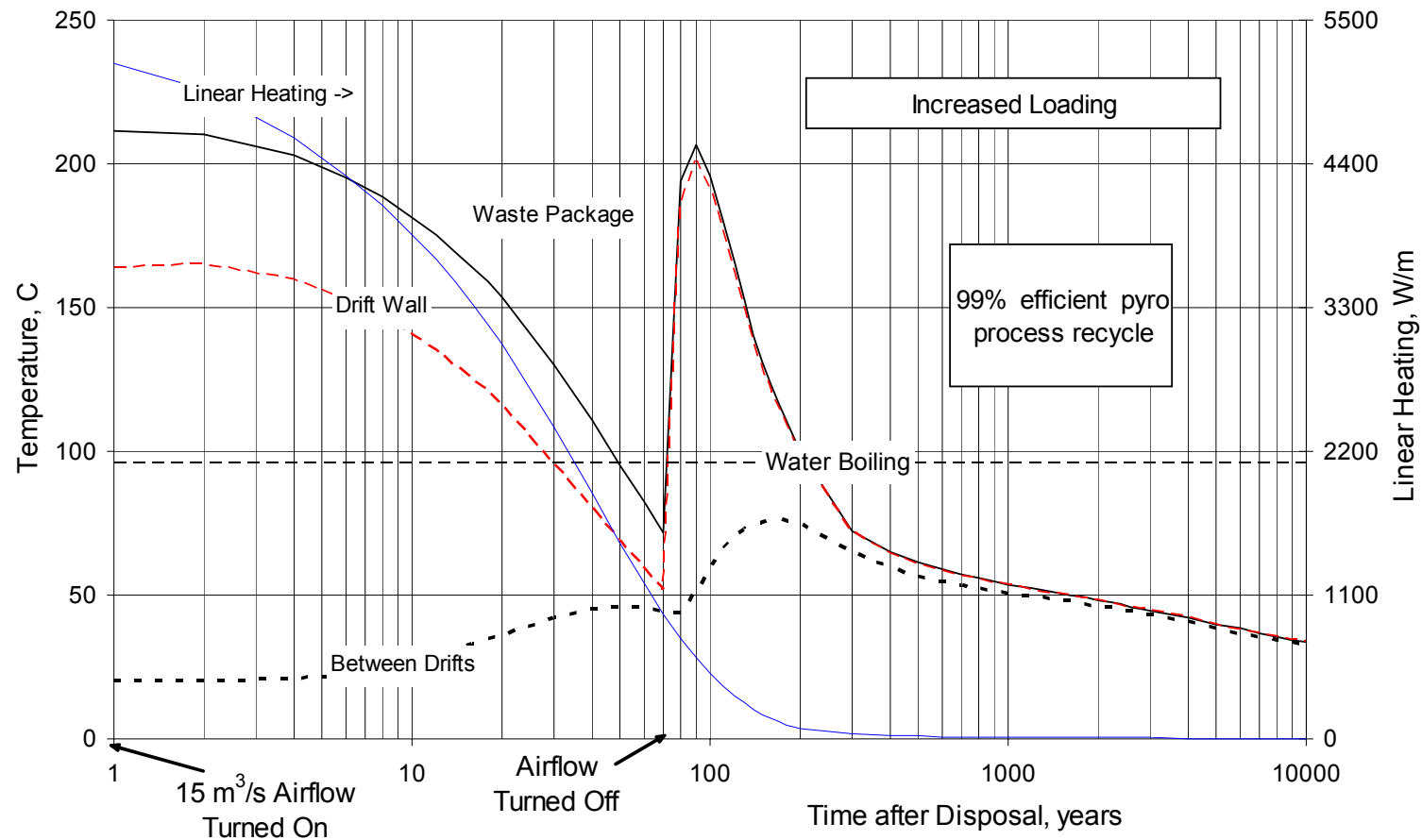
- Recommendations
 - Studies need to be completed
 - *Systematic approach*
 - *Various heat load management scenarios*

Repository Transient Thermal Response



Transient Response w/o Pu and Am

Computed Repository Temperatures for Disposal of 10 Year Old
Recycle AFR/PWR Fuel (Increased Loading)



Recycle in LWR's

Objective was to define optimum number of recycle (Pu) in LWR's

- **Increasing the number of recycle reduces the size of Tier 2**

But

- **Cost of recycle might increase at each pass?**
- **Accumulation of MA's increases**

There is insufficient data to conclude.

But there is no emergency to decide, as the first recycle for the existing inventory will not be concluded for 40 to 50 years!

First cycle technologies will be available, and adequate, if needed.

Cm Storage or Recycle

- **Storage, decay, and later transmutation**
- **Recycle with Am**
 - Storage has been extensively studied by Japanese program
 - Storage is judged to be uselessly cumbersome
 - *Small quantities*
 - *Expensive separations*
 - *Complex storage*

Criterion	Basis	Thermal Recycle of Pu/Np, Fertile Fuel	Thermal Recycle, Non-Fertile Fuel	FR Recycle of Uranium and All TRUs
Recovery Efficiency Criteria				
U recovery efficiency (assuming all U lost goes to HLW stream)	Cost of makeup U	90%	n/a (1)	4% (2)
	HLW volume (cost of MPCs)	90%	90%	90%
Pu/Np recovery efficiency (assuming all Pu/Np lost goes to HLW stream)	Long-term radiotoxicity reduction (X100)	99%	99%	99%
	Off-site dose reduction (X100)	99%	99%	99%
MA recovery efficiency (assuming all MA lost goes to HLW stream)	Long-term heat load reduction (X100)	99.5%	99.5%	99.5%
	Off-site dose reduction (X100)	99%	99%	99%
Cs/Sr recovery efficiency (assuming all Cs/Sr lost goes to HLW stream)	Short-term heat load reduction (X100)	99%	99%	99%
	Reduction to equal heat load from other residual fission products (to a total of ca. 50 watts/t 30-y SNF)	97%	97%	97%
Product Stream Purification Criteria				
U purification	Disposal as LLW (10CFR61.55)	(3)	(3)	(3), (4)
	Conversion to UF ₆ and re-enrichment (ASTM C 788-98)	(5)	(5)	(5)
	Use in MOX fuel	(6)	(6)	n/a
Pu/Np purification	Use in MOX fuel	(7)	n/a	n/a
	Use in non-fertile fuel	n/a	(7)	n/a
U/TRU purification	Use in FR fuel	n/a	n/a	(8)
Cs/Sr purification	Ultimate disposal as LLW	<100 nCi TRU/g	<100 nCi TRU/g	<100 nCi TRU/g
LLFP Recovery Criteria				
Tc recovery efficiency (assuming all Tc lost goes to HLW stream and is not immobilized)	Off-site dose reduction (X20)	95%	95%	95%
I recovery efficiency (assuming all I lost goes to HLW stream and is not immobilized)	Off-site dose reduction (X20)	95%	95%	95%
LLFP Purification Criteria				
Tc purification	For transmutation purposes (to avoid further Tc production by fission) - limit production rate to 10% of transmutation rate	(9)	(9)	n/a for pyro (place in durable waste form)
I purification	For transmutation purposes (to avoid further I production by fission) - limit production rate to 10% of transmutation rate	(10)	(10)	n/a for pyro (place in durable waste form)
Gaseous FP Recovery Criteria (Kr, Xe, T, C-14, I)	TBD	TBD	TBD	TBD

NOTES

- (1) - No uranium in fuel
- (2) - Only 85 t U required for fab. of FR fuel from all TRUs present at 2000 t CLWR fuel per year
- (3) - all in nCi/gU: Tc-99<693; I-129<18.5; Sr-90<1.6E06; Cs-137<1.1E06; TRU($T_{1/2}$ <5y)<118; Pu-241<4127; Cm-242<2.4E04
- (4) - total gamma emitters <3E05 Bq/g U; to facilitate unshielded storage of U for future use
- (5) - all in nCi/gU: Tc-99<8.5; Np<3.38; TRU<6.76; FP gamma<12.25; Other impurities (Al, Ba, Bi, Cd, Ca, Cu, Fe, Pb, Li, Mg, Mn, Ni, K, Ag, Na, Sr, Th, Sn, Zn, Zr) to sum <500 microgm/gU; lanthanide content <3 mg/gHM
- (6) - see ASTM C 833-01; lanthanide content <3 mg/gHM
- (7) - see ASTM C 757-90; lanthanide content <3 mg/gHM
- (8) - lanthanide content <20 mg/g U/TRU (FCCI limit); Am/Cm content <20 mg/g U/TRU (heat generation during fuel fab); Pu-238 content <10 mg/g U/TRU (heat generation during fuel fab)
- (9) - less than 1.63E-05 g fissile actinides per g Tc-99
- (10) - less than 3.84E-06 g fissile actinides per g I-129